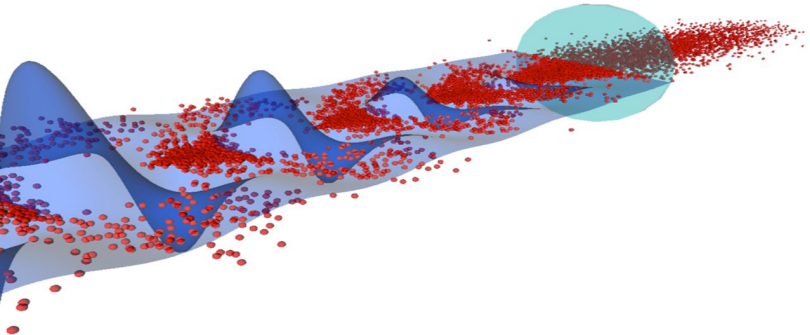
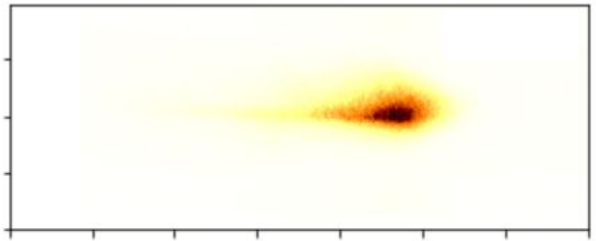
An experimental study of transverse and longitudinal wakefields driven by a self-modulating proton bunch

Marlene Turner for the AWAKE collaboration





Outline

- Introduction to the **AWAKE** Experiment
- Wakefield **Measurements**
  - Concept, Challenges
- **Results**
- Conclusion & Summary

Introduction to AWAKE

- AWAKE stands for: **A**dvanced (Proton Driven Plasma) **WAK**efield **E**xperiment.
- AWAKE is a **R&D project** to study proton driven plasma wakefields at CERN.
- **Final Goal:** Design high quality & high energy electron accelerator.

Why protons?

Highly-relativistic proton bunches (e.g. at CERN) have the potential to drive wakefields that can accelerate a witness bunch to TeV energies in a single plasma.

Caldwell A., *Nature Physics* **volume 5**, pages 363–367 (2009)

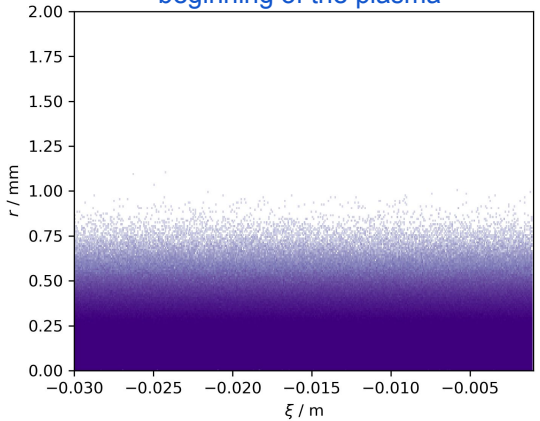
10m Rb vapor cell developed by MPP

Seeded Self-Modulation

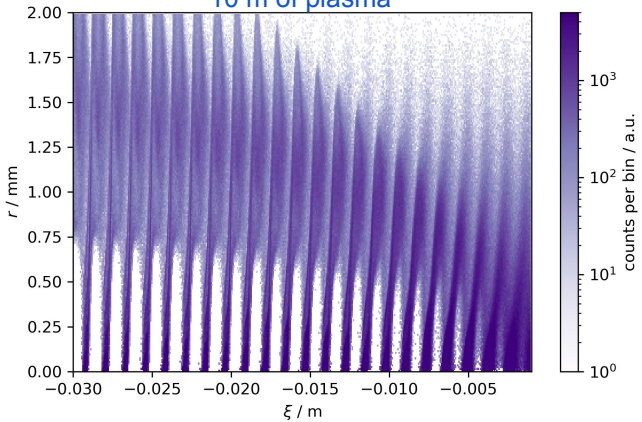
AWAKE Run 1, Phase 1
(2016, 2017)

all simulations performed with LCODE (2D cylindrical, quasistatic)

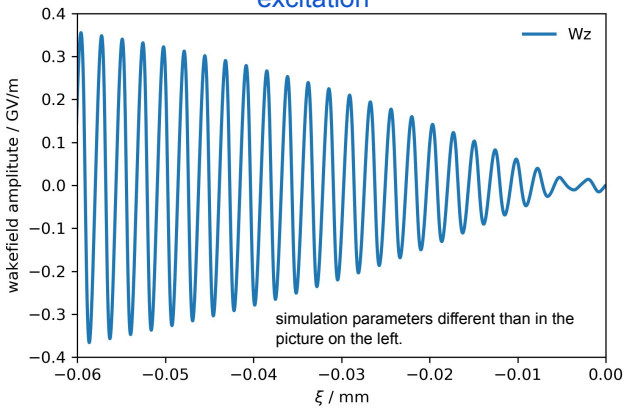
proton bunch density in the beginning of the plasma



proton bunch density after 10 m of plasma



resonant wakefield excitation



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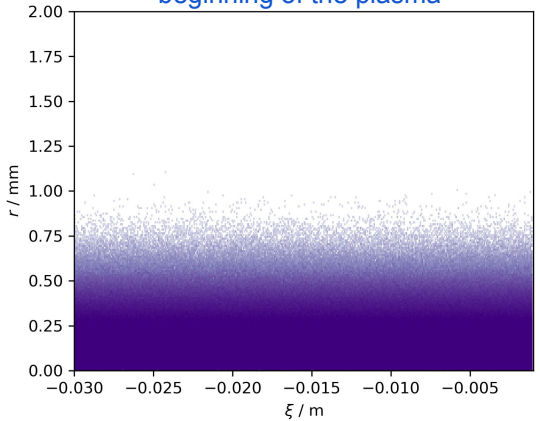

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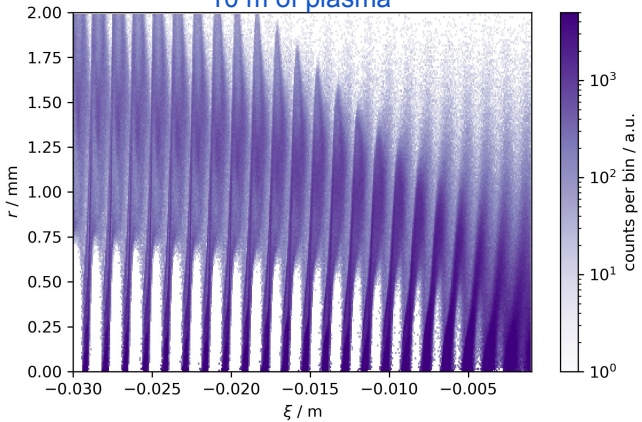

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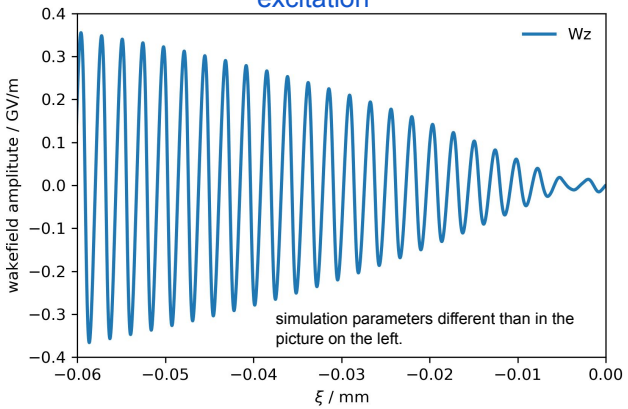
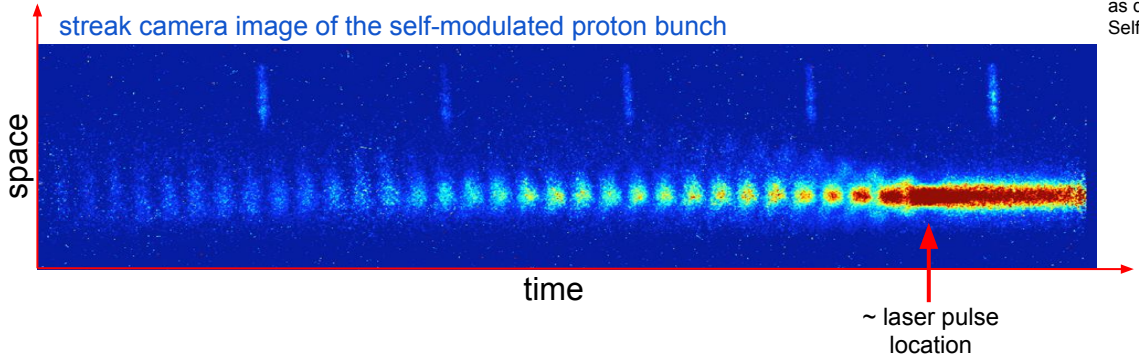


streak camera image of the self-modulated proton bunch



as discussed in the plenary session on Monday (Proton Bunch Self-Modulation and Electron Acceleration in AWAKE by P. Muggli, 12:00)

proton bunch self-modulation and resulting wakefield amplitude growth has been experimentally demonstrated:

AWAKE Collaboration Phys. Rev. Lett. 122, 054802
M. Turner *et al.* (AWAKE Collaboration); Phys. Rev. Lett. 122, 054801

M. Turner
for the AWAKE collaboration

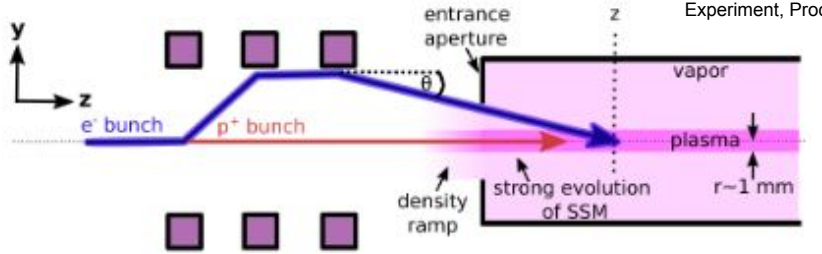
Electron Acceleration

AWAKE Run 1, Phase 2 (2018)

electron delay ~100-800 ps wrt to the ionizing laser pulse

oblique electron injection:

See details in: M. Turner et al., External Electron Injection for the AWAKE Experiment, Proceedings of AAC 2018.

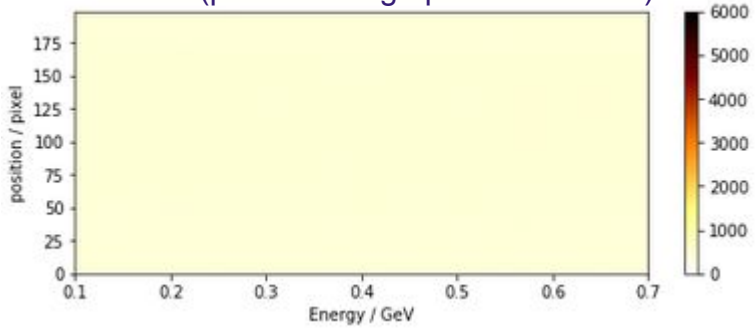


1) Short plasma density ramp at the entrance of the plasma
   ⇒ change of wakefield phase
2) During the SSM the proton bunch distribution evolves

Electron Acceleration

AWAKE Run 1, Phase 2 (2018)

Electrons off (protons & high power laser on)



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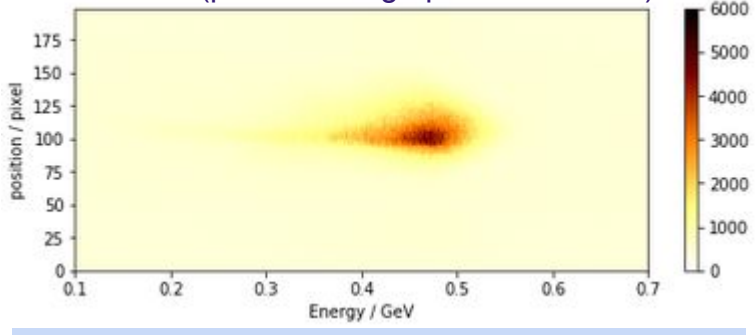
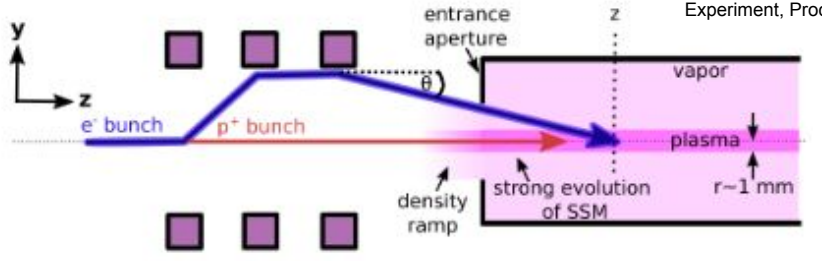


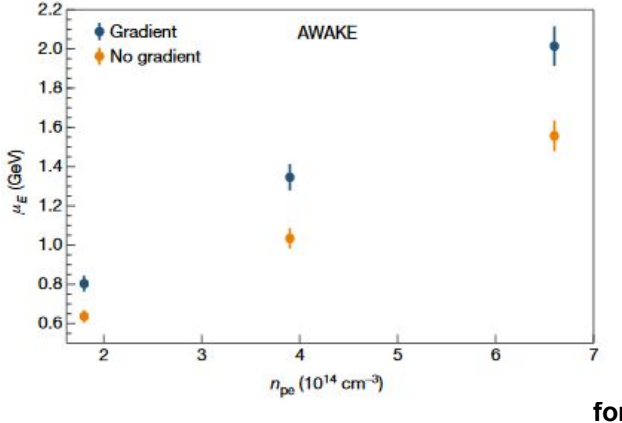
- electron acceleration in wakefields driven by a self-modulating proton bunch
- finite electron energy spread
- GeV acceleration (up to ~2 GeV, from ~20 MeV)

electron delay ~100-800 ps wrt to the ionizing laser pulse

oblique electron injection:

See details in: M. Turner et al., External Electron Injection for the AWAKE Experiment, Proceedings of AAC 2018.





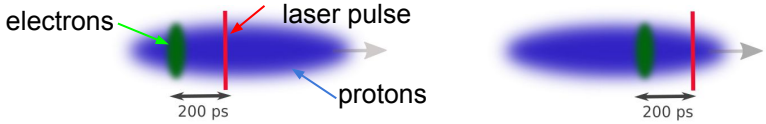
AWAKE Collaboration, *Nature* **volume 561**, pages 363–367 (2018).

M. Turner
for the AWAKE collaboration

Measurement Concept

all simulations performed with
LCODE (2D cylindrical, quasistatic)

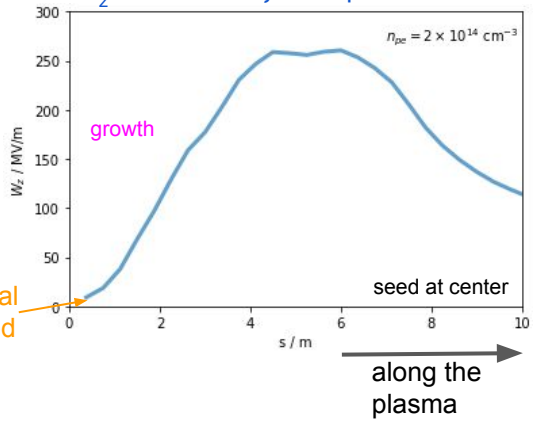
wakefields amplitudes along the 10m plasma in AWAKE

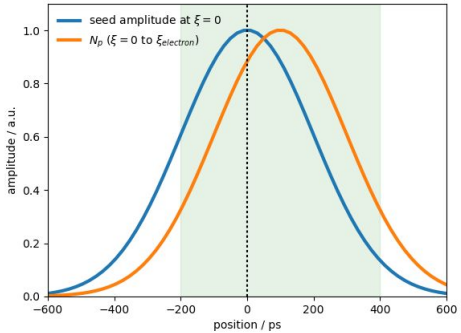


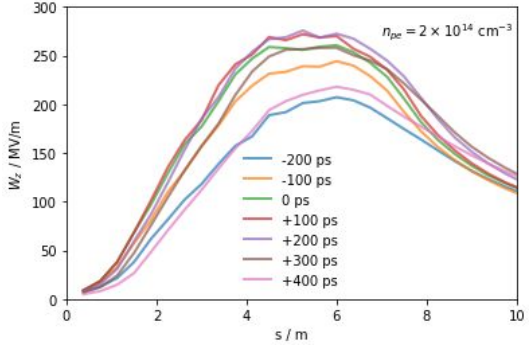
How to measure?

longitudinal

W_z at r = 0 and ξ= -200ps







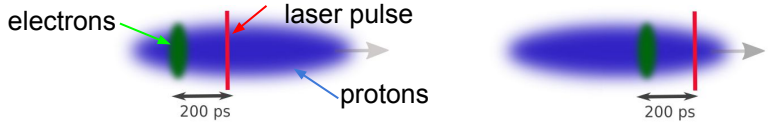
accelerate electrons

M. Turner
for the AWAKE collaboration

Measurement Concept

all simulations performed with
LCODE (2D cylindrical, quasistatic)

wakefields amplitudes along the 10m plasma in AWAKE



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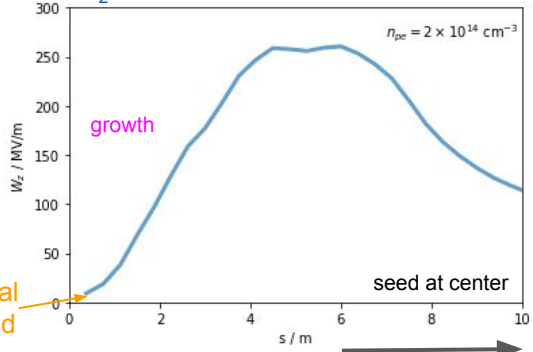
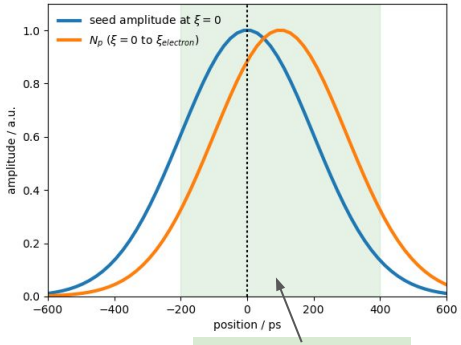
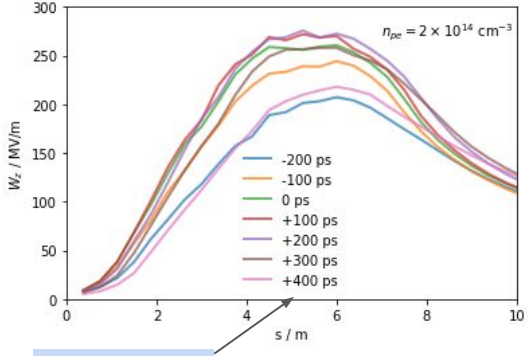


initial seed

along the plasma



measured range

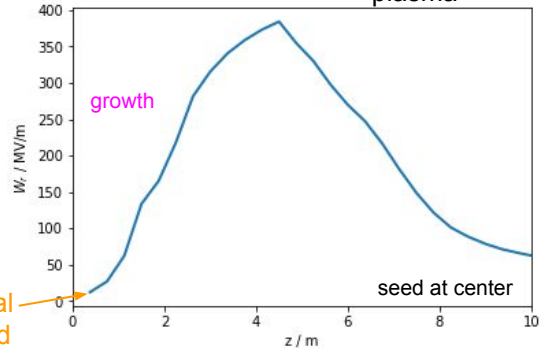


seed position

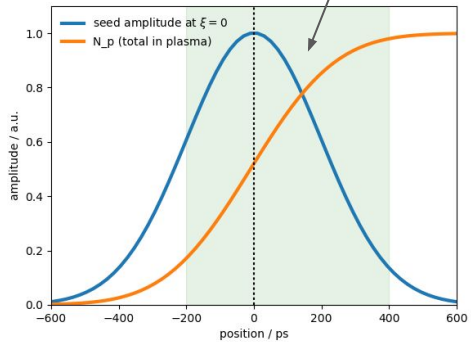
accelerate electrons

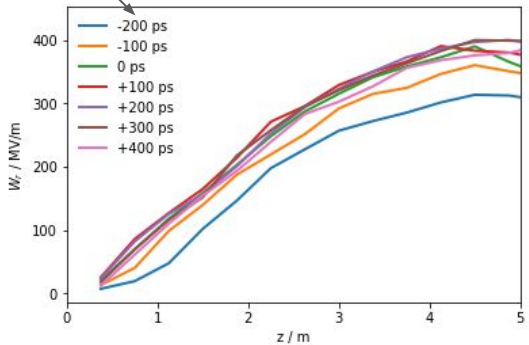
transverse

W_r at r = σ_r and ξ_{max}



initial seed





measure radial proton bunch distribution

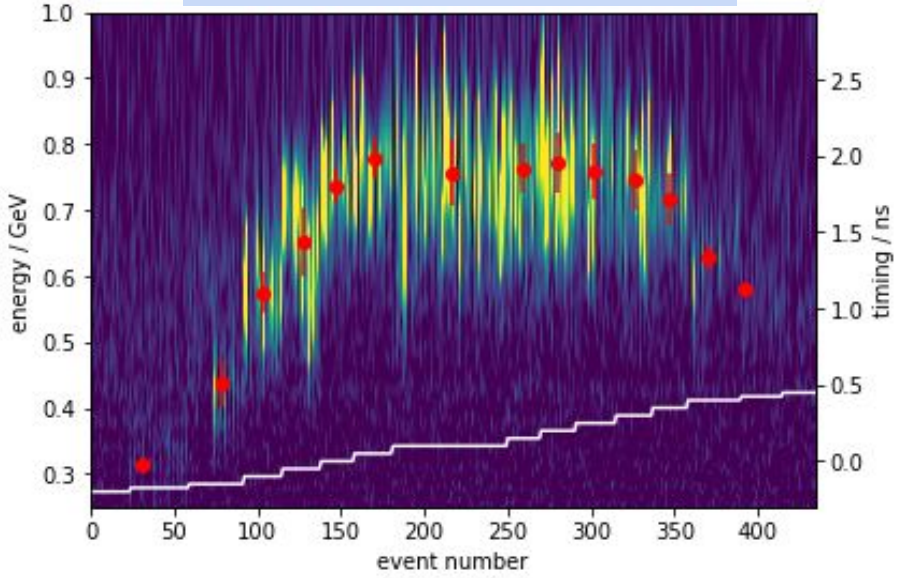
Seed Position Scan

longitudinal wakefields

Preliminary

change laser pulse and electron bunch position together

waterfall plot of the measured electron energy spectrum as a function of the laser pulse seed position



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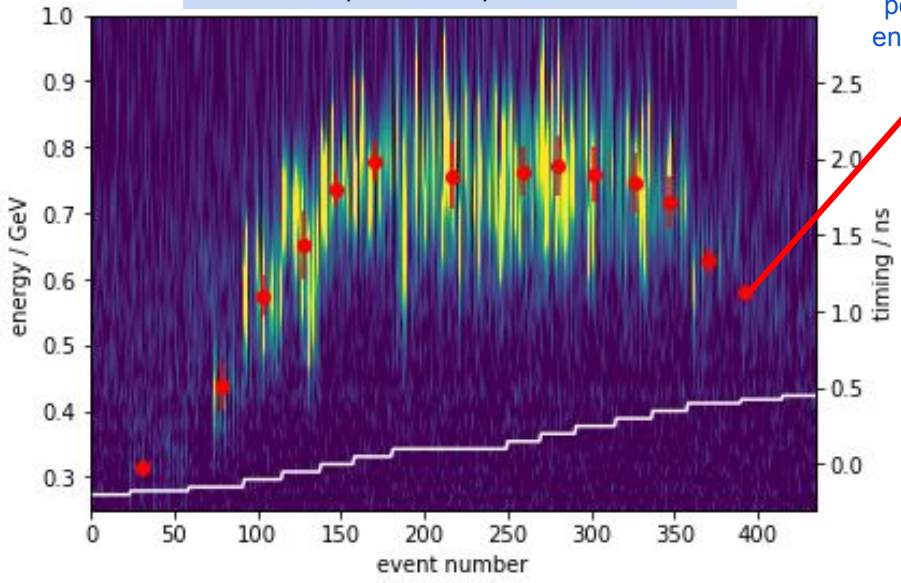
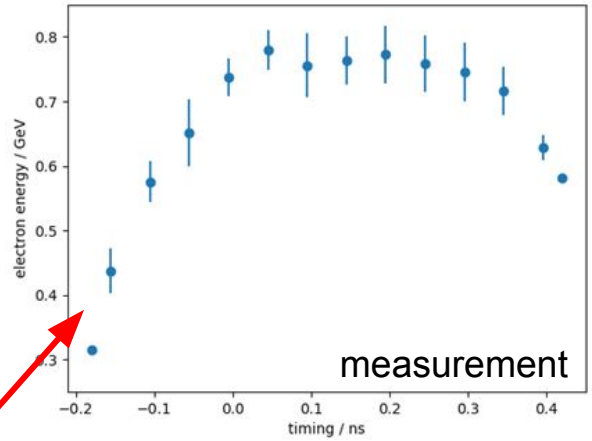
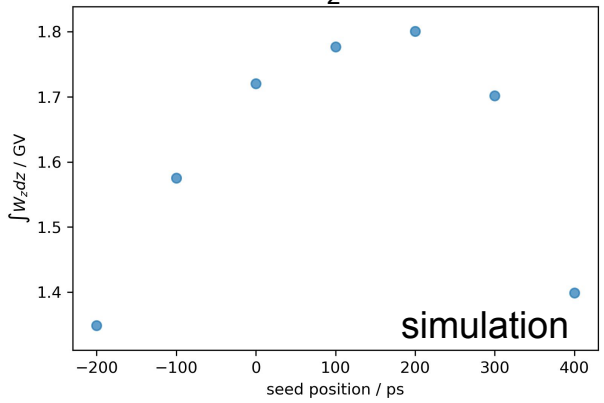


identify the peak energy



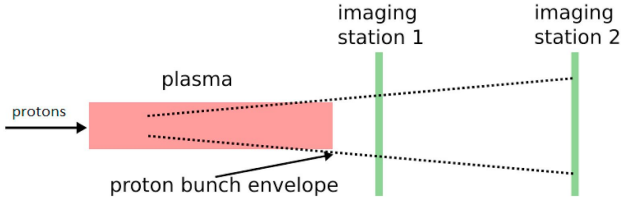
integral of W_z (over 10 m)

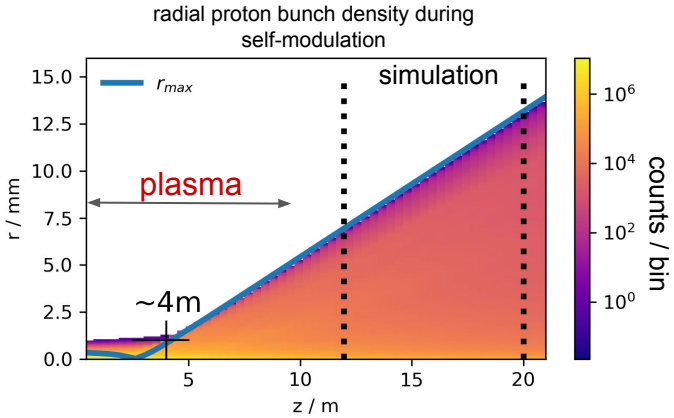


measured peak electron energy follows the same shape as the integrated longitudinal wakefield amplitude!

Seed Position Scan
transverse wakefields

Measurement setup:





M. Turner, PhD Thesis (2018).
M. Turner et al., J. Phys.: Conf. Ser.874 012031 (2017).
M. Turner (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801 (2019).

Seed Position Scan
transverse wakefields

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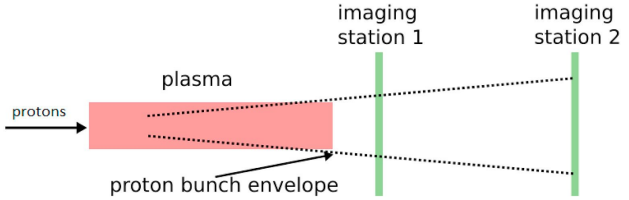
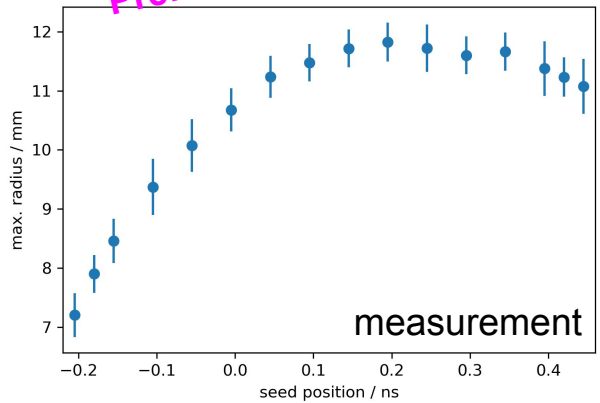


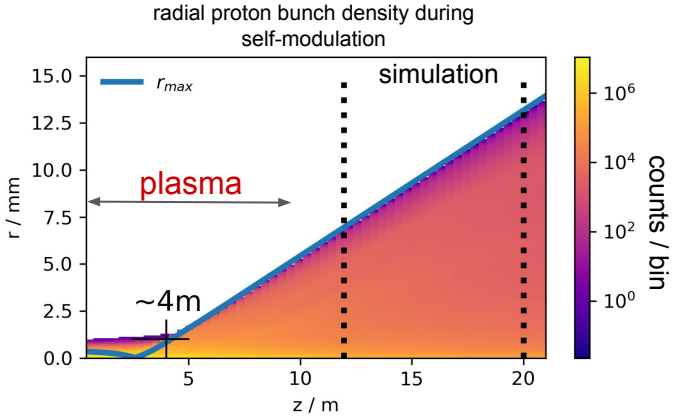
measure maximum radius of defocused protons

M. Turner et al., NIM A 909 (2018), 123-125.

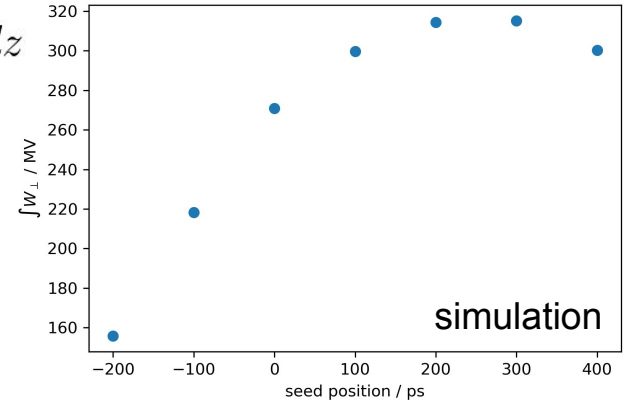
Preliminary

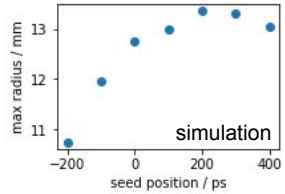


maximum radius of the defocused protons follows the same shape as the integrated (0-4m) transverse wakefield amplitude!



$$\int_{0m}^{4m} W_r dz$$





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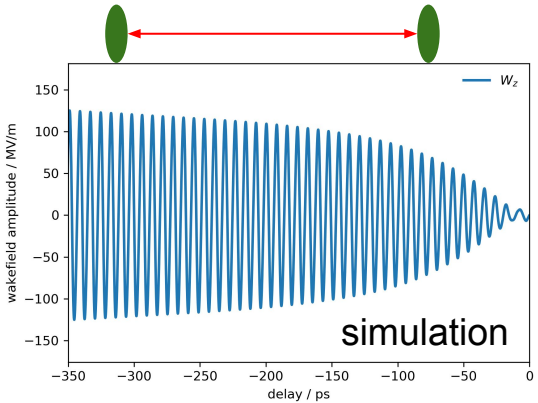
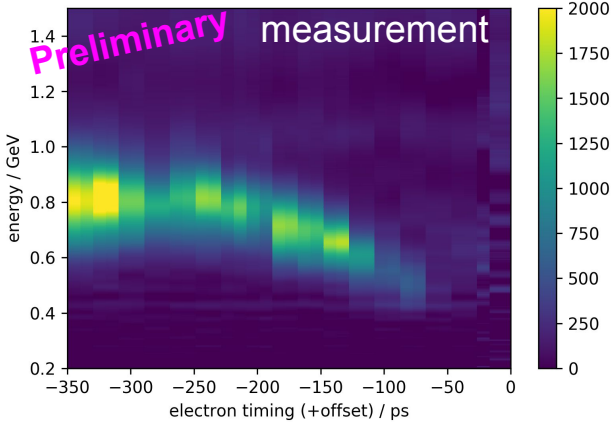
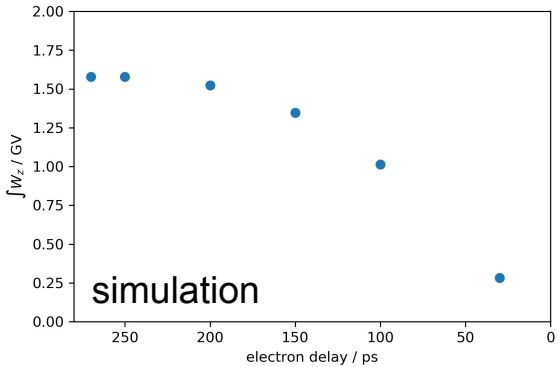
Electron Delay Scan

longitudinal wakefields

change the delay (0-800 ps) between the electron bunch and the laser pulse:







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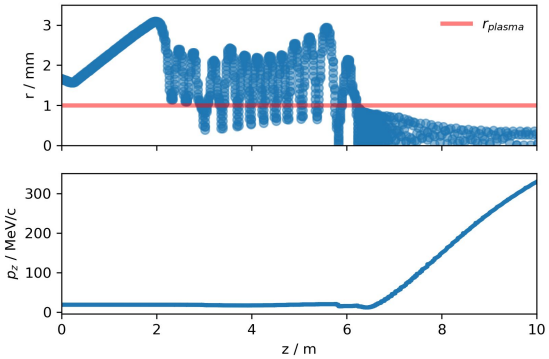
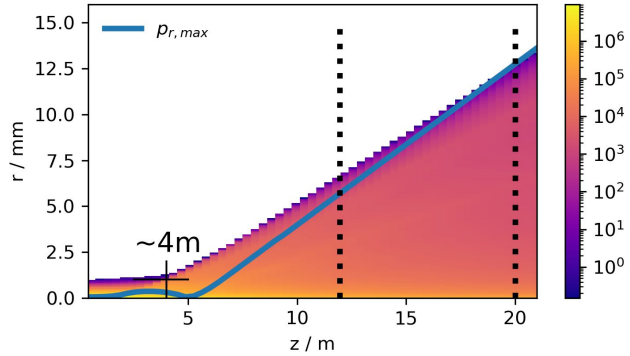
Ongoing studies...

electron acceleration dynamics



electron dynamics complicated as wakefields phase is evolving along the plasma due to the self-modulation process

defocused proton trajectories



where do protons exit? which ones are the outermost on the screen?

Conclusions & Summary

- AWAKE is a **proton driven** plasma wakefield experiment.
- The **self-modulating** proton bunch resonantly drives wakefields in the 10 m long plasma.
- We probe and study the **longitudinal wakefields** by externally injecting electrons.
- We probe and study the **transverse wakefields** by looking at the transverse proton bunch distribution downstream the plasma.
- The measured **dependencies** (on seed position and electron delay) scale with the simulated wakefield amplitudes, confirming the expected physics scalings.